9. SUMMARY AND CONCLUSIONS

Risk assessment is inherently an attempt to anticipate the impact of future events. Because the events that might take place sometime in the future are infinite, no risk analysis can examine all of the possible sequences of events that might characterize the activity of interest, here the transport of spent fuel. Risk analysts address this problem by constructing representative sets of data for each important characteristic of the activity of interest. Then, by estimating the outcomes for all possible combinations of the representative sets of data, a set of outcomes (here the radiological consequences associated with the transport of spent fuel) is developed that is expected to adequately explore the range and variability of the space that contains the infinity of possible outcomes.

Cask design, route characteristics (e.g., accident rates and on-route and wayside population densities), package external dose rates, prevailing weather, accident source terms, and evacuation times are the principal characteristics of spent fuel shipments that affect the radiological consequences associated with spent fuel shipments. For this study, three representative sets of data were developed. The first set developed generic design data for four representative casks, steel-lead-steel truck and rail casks, a steel-DU-steel truck cask, and a monolithic steel rail cask. The second set contained 200 sets of representative truck or rail route data. Associated with each representative set of route data was one possible set of prevailing weather conditions, an external package dose rate, and an evacuation time. The values of these parameters were selected by structured Monte Carlo (Latin Hypercube) sampling from distributions of these parameter values that were derived from actual routes that might be used in spent fuel shipping campaigns. The third set contained 19 representative truck or 21 representative train accident source terms developed by analysis of the

- response of spent fuel casks, including the cask closure, and of the spent fuel rods being transported in the cask to the mechanical and thermal environments that the cask might experience during collision and fire accidents;
- size of the cask leak and the numbers of spent fuel rods that might fail due to these mechanical and thermal environments; and
- amounts of radioactive materials that would escape from the failed rods to the cask interior and then be released through the cask leak path to the environment before being deposited onto cask interior surfaces.

Cask response to mechanical (collision) loads was estimated from the results of finite element calculations. These calculations examined the impact of each of the four generic casks onto an unyielding surface at three impact orientations. The impact speed onto a yielding surface that would cause the same cask damage as was predicted for the impact onto the unyielding surface was then estimated by partitioning the available impact energy between the cask and the yielding surface. Cask response to thermal loads, specifically the times required to heat the cask seal to seal decomposition temperatures and spent fuel rods to burst rupture temperatures, were estimated by performing one-dimensional thermal analyses of the cask shell that took account of the cask neutron shield compartment and the decay heat load produced by the spent fuel being carried in the cask.

These impact and thermal results were used to estimate the dependence of cask leak areas on collision speed and on the heating times required for an engulfing hydrocarbon fuel fire to heat the cask to temperatures where elastomeric seals are seriously degraded or rods burst rupture. Leak areas were used to estimate cask depressurization times following pressurization due to failure of spent fuel rods. The depressurization time estimates then allowed cask-to-environment release fractions to be estimated from the results of another study that examined transport of noble gases, condensible vapors, and aerosols from a TN-12 cask through leak paths with various cross-sectional areas to the environment. The results of that study show that, when cask leak areas are small, cask depressurization is slow. Thus, considerable time is available during which particles and condensible vapors can deposit onto cask interior surfaces. Conversely, when cask leak areas are large, the rapid flow of gases out of the cask carries most materials released from failed rods out to the environment before they can deposit onto cask interior surfaces. Total release fraction values were calculated by combining the values estimated for cask-to-environment release fractions with rod-to-cask release fraction values based on the experimental results of Lorenz.

The fraction of all accidents that might produce a given source term was estimated using the Modal Study truck and rail accident event trees, accident speed distributions, and accident fire duration distributions. Because only impact onto hard rock at high speed appears to be able to cause a spent fuel cask to leak, the Modal Study event trees were updated to reflect the frequencies of occurrence of hard rock along three long interregional transportation routes as determined by GIS analyses.

Given this input data, the radiological consequences associated with the shipment of spent fuel were then estimated by performing RADTRAN calculations. Two types of radiological consequences were examined: (1) consequences attributable to the population exposures that result from the external dose rate of the undamaged package (incident-free consequences), and (2) consequences caused by accidents that lead to the release of radioactive materials from the damaged cask (accident consequences). Consequences were calculated for PWR and BWR spent fuel shipped in each generic cask via each of the 200 routes in the representative sets of input data, for four illustrative real truck and real rail routes, and for the NUREG-0170 truck and rail routes. All of these calculations used the representative sets of 19 truck and 21 rail accident source terms developed by this study.

The results obtained for the four generic casks using the 200 representative routes and the representative truck and rail accident source terms showed that accident dose risks are negligible when compared to incident-free dose risks, that truck transport stop doses exceed all other truck incident-free doses, and that all other rail incident free doses are comparable in magnitude to rail stop doses. These calculations also showed that for each transport mode the results obtained for the illustrative routes and the NUREG-0170 route fall within the range of results generated by the representative sets of 200 truck or rail routes.

The dependence of accident consequences on accident source terms was examined further by comparing the results of calculations that differed only in the source terms used. Four sets of truck and four sets of rail accident source terms were examined: the NUREG-0170 Model I and Model II source terms, the Modal Study sets of 20 truck and 20 rail accident source terms, and the sets of 19 truck and 21 rail accident source terms developed by this study. Comparison of the mean (expected) accident population dose risks produced by these calculations indicates that, for truck accidents, the NUREG-0170 Model I risks are about 17 times larger than NUREG-0170 Model II risks, which are about 6 times larger than the risks estimated using Modal Study truck accident source terms, which in turn are about 160 times larger than the risks estimated using the truck accident source terms developed by this study. For rail transport, NUREG-0170 Model I accident population dose risks are about 10 times larger than the rail accident risks estimated using Modal study rail accident source terms, which are about 4 times larger than the risks estimated using NUREG-0170 Model II source terms, which are about 50 times larger than the risks estimated using the rail accident source terms developed by this study.

The relative ordering of these accident results is entirely consistent with the assumptions made by each study regarding the probability of radionuclide release during transportation accidents and the magnitude of the source terms generated by accidents of differing severities. Because NUREG-0170 assumed that spent fuel casks might fail when subjected to the loads that characterize minor accidents, the fraction of all truck and train accidents estimated to lead to cask failure is very large and extremely conservative. Similarly, because the NUREG-0170 Model I assumed that all cask failures allowed the entire NUREG-0170 accident inventory (the maximum amount of radioactivity that could be released during an accident) to be released, NUREG-0170 Model I mean accident population doses for truck and rail accidents are quite large. The Modal Study estimated cask leakage from the response of the cask shell to mechanical and thermal loads. As a result, both source term probabilities and source term magnitudes decrease and the accident population dose risks calculated using these source terms are one or two orders of magnitude below those calculated using NUREG-0170 source terms. In this study, source term probabilities and magnitudes were estimated by examining the response of cask closures and spent fuel rods to impact loads, and the burst rupture of spent fuel rods due to heating by fires. Based on this more detailed analysis, cask leakage is found to be even less likely than the estimates of the Modal Study, and retention of particles and condensible vapors by deposition onto cask interior surfaces is found to be substantial. Accordingly, both source term probabilities and magnitudes decrease further, and consequently accident population dose risks are reduced further by factors of 10 to 100.

This summary and the detailed analyses described in Sections 2.0 through 9.0 lead to the following conclusions:

- The single cask truck shipment expected incident-free population doses developed by this study are about one-quarter of those in NUREG-0170.
- The single cask rail shipment expected incident-free population doses developed by this study are about two-thirds of those in NUREG-0170.

- The use of very conservative cask failure criteria in NUREG-0170 caused its estimates of the fraction of all accidents that release radioactive materials to be much too large and thus very conservative.
- The NUREG-0170 estimate of the largest source term that might be released from a failed spent fuel cask during an unusually severe transportation accident is significantly lower than the largest source terms calculated using Modal Study release fractions or the release fractions developed by this study. However, the risks associated with these source terms are lower than the risk of the largest NUREG-0170 source term because these source terms are so very improbable.
- The source terms developed by the Modal Study and by this study, which reflect the complexities of rod failure and cask response to transportation accident impact and thermal loads, yield estimates of expected (mean) spent fuel transportation accident population doses that are orders of magnitude smaller than those developed by the NUREG-0170 study.

Consequently, the results of this study show that the NUREG-0170 estimates of spent fuel transportation incident-free doses are somewhat conservative and the NUREG-0170 estimates of accident population dose risks are very conservative. Since the NUREG-0170 dose and risk estimates were not large enough to require regulatory action, the fact that the incident-free doses estimated by this study are significantly smaller than the NUREG-0170 estimates and the accident dose risks estimated by this study are orders of magnitude smaller than those estimated by NUREG-0170 confirms that spent fuel transportation regulations adequately protect public health and safety.